LA-UR- 02-6497

Approved for public release; distribution is unlimited.

Title: 3D Analysis of Bainite Morphologies and Kinetics in Alloy STeels

Author(s): R.E. Hackenberg
D.P. Nordstrom
G.J. Shiflet

Submitted to: TMS Fall Meeting, Columbus, OH, 6-10 October 2002

2002 TMS Fall Meeting, Columbus, OH, 6-10 October 2002

Symposium on the Characterization and Representation of Material Microstructures in 3-D

3D Analysis of Bainite Morphologies and Kinetics in Alloy Steels

R.E. Hackenberg[1], D.P. Nordstrom[2] and G.J. Shiflet[2]

[1]Materials Science and Technology Division (MST-6)
Mail Stop G770
Los Alamos National Laboratory
Los Alamos, NM 87545

[2]Department of Materials Science and Engineering
University of Virginia
Charlottesville, VA 22904-4745

Abstract

Serial sectioning and 3D reconstruction of austenite decomposition products were undertaken in bayforming ternary steels to better understand their true morphologies in the bay region of their TTT diagrams. Jagged growth interfaces are revealed in allotriomorphic bainite formed at the bay in Fe-0.24C-4Mo, contrasting with the idealized geometries often assumed when formulating growth models. This also has implications for experimental thickening kinetics measurments. Examination of the so-called "degenerate" ferrite formed below the bay in Fe-0.3C-6.3W reveals that it is not degenerate at all, but rather has a Widmanstatten rod morphology which gives the appearance of degeneracy due to the multiplicity of ways that they can intersect a randomly-oriented plane of polish. Furthermore, these rods are grouped in packets posessing a common elongation direction, highlighting the crystallographic nature of their formation. The impact of these findings on the understanding of austenite decomposition in bayforming steels will be discussed.

3-D Analysis of Bainite Morphologies and Kinetics in Alloy Steels

R.E. Hackenberg

Materials Science and Technology Division
Los Alamos National Laboratory

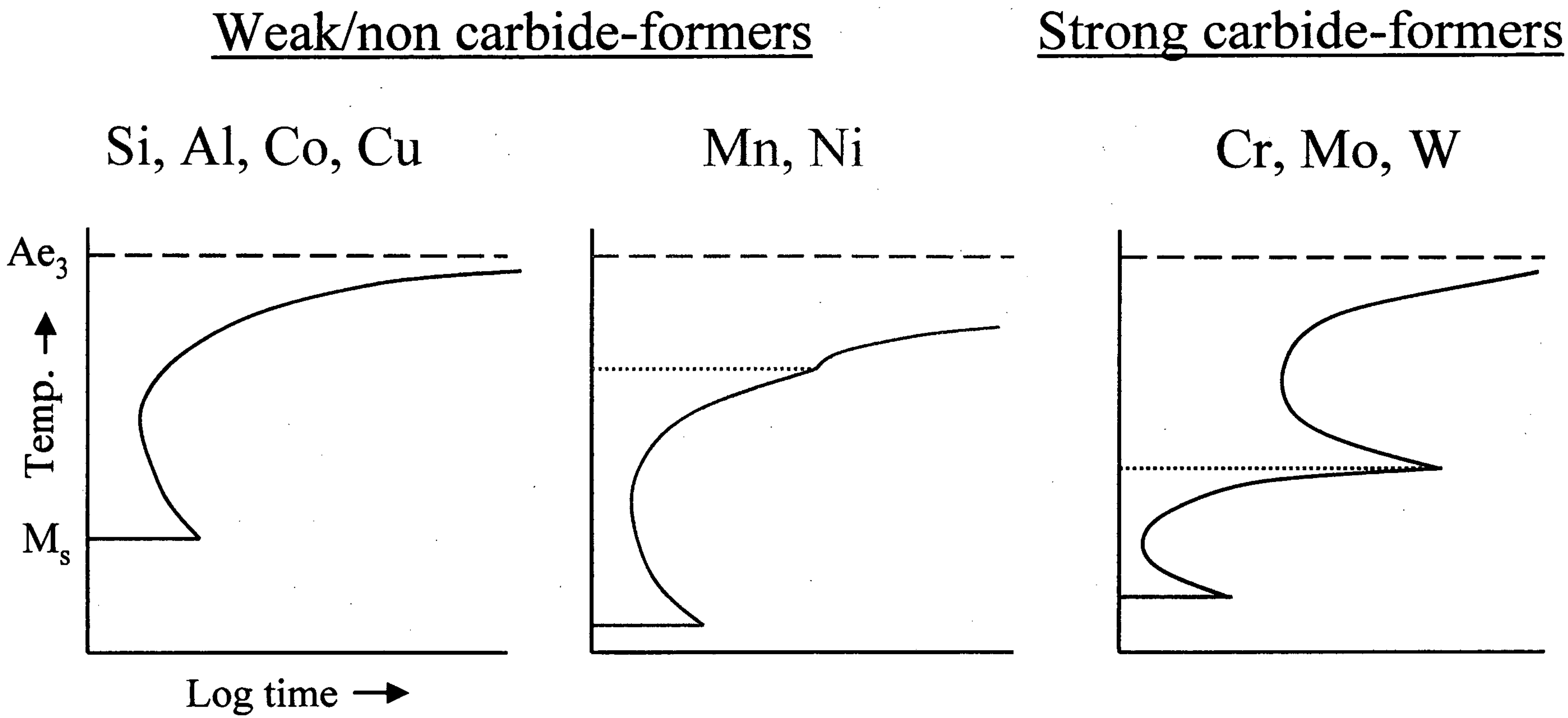
D.P. Nordstrom, G.J. Shiflet

Department of Materials Science and Engineering
University of Virginia

Acknowledgements

National Science Foundation
Derren Dunn

TTT Diagram Shapes in Low-C Fe-C-M Steels



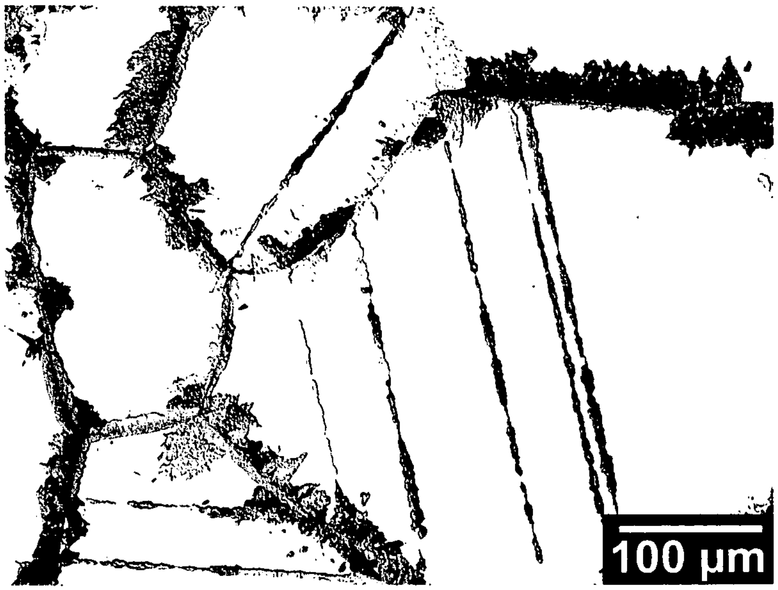
Bainite in Bayforming Fe-C-M Steels

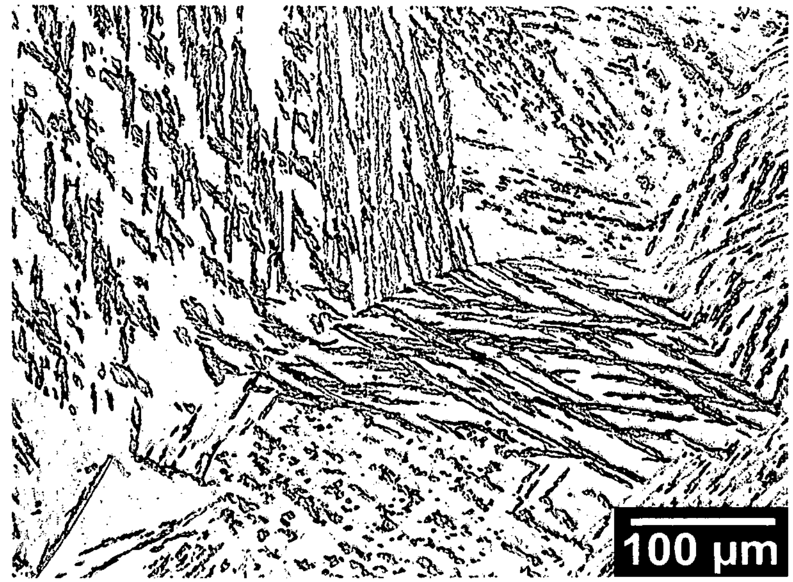
At/Above Bay

- GB and TB Allotriomorphs
- Slow Bainite Thickening

Below Bay

- Intragranular "Degenerate"
- Transformation Stoppage





560°C-21 days

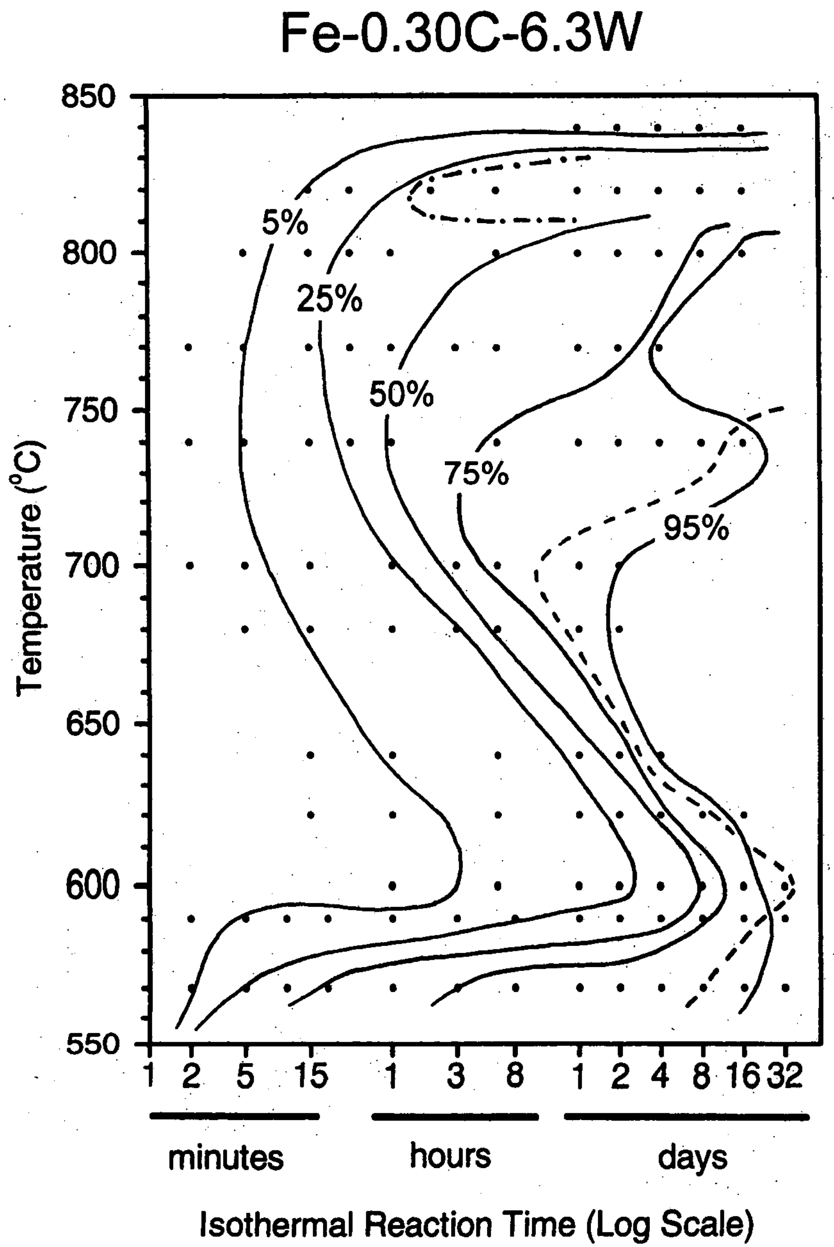
Fe-0.24C-4Mo

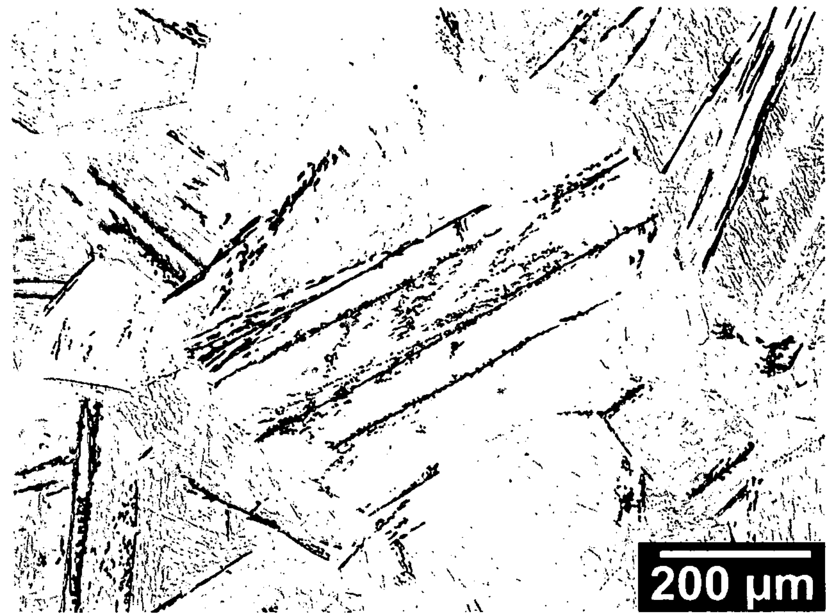
550°C-16 hr

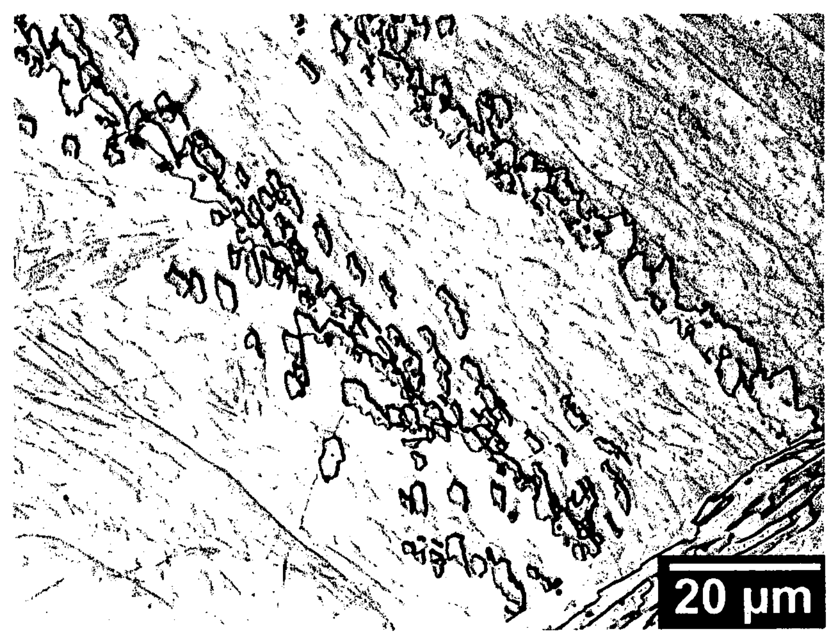
Serial sectioning can illuminate

- Slow thickening above bay
- True morphology below bay

Part I: Morphology of Bainite Below the Bay

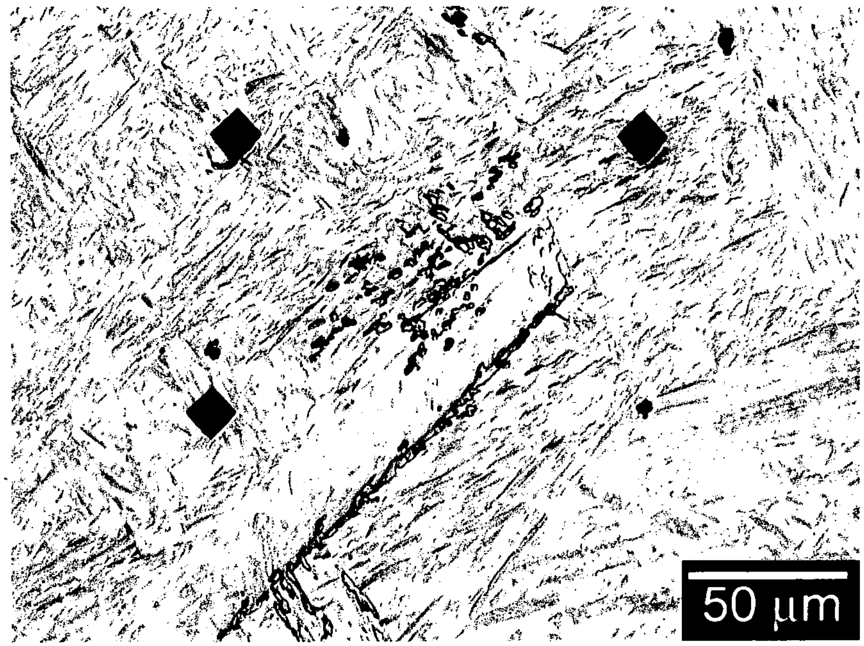


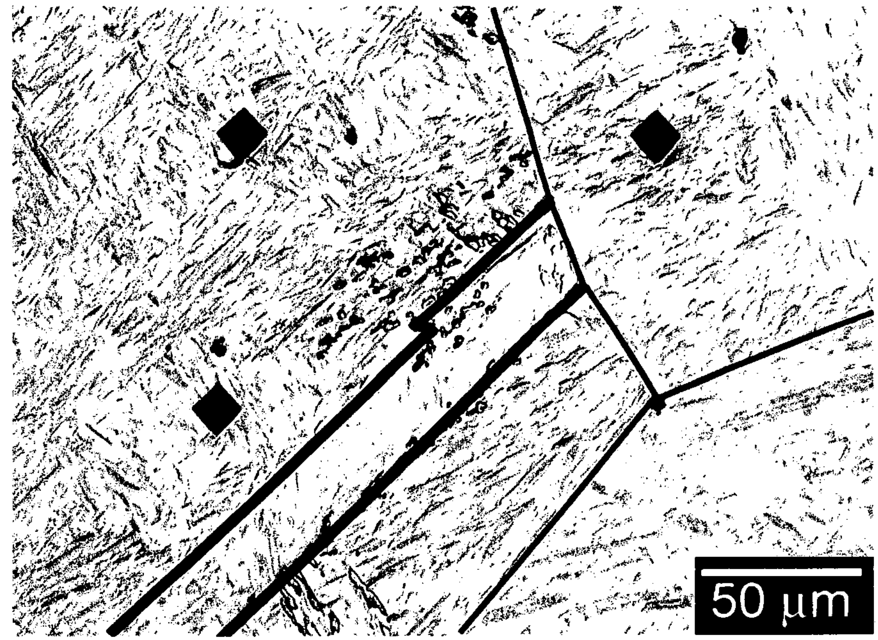




Sectioning

- HV indents placed
- 1 μm alumina polish, nital etch, digital imaging
- 81 sections, 10.4 μm total depth removed (0.13 μm/slice)

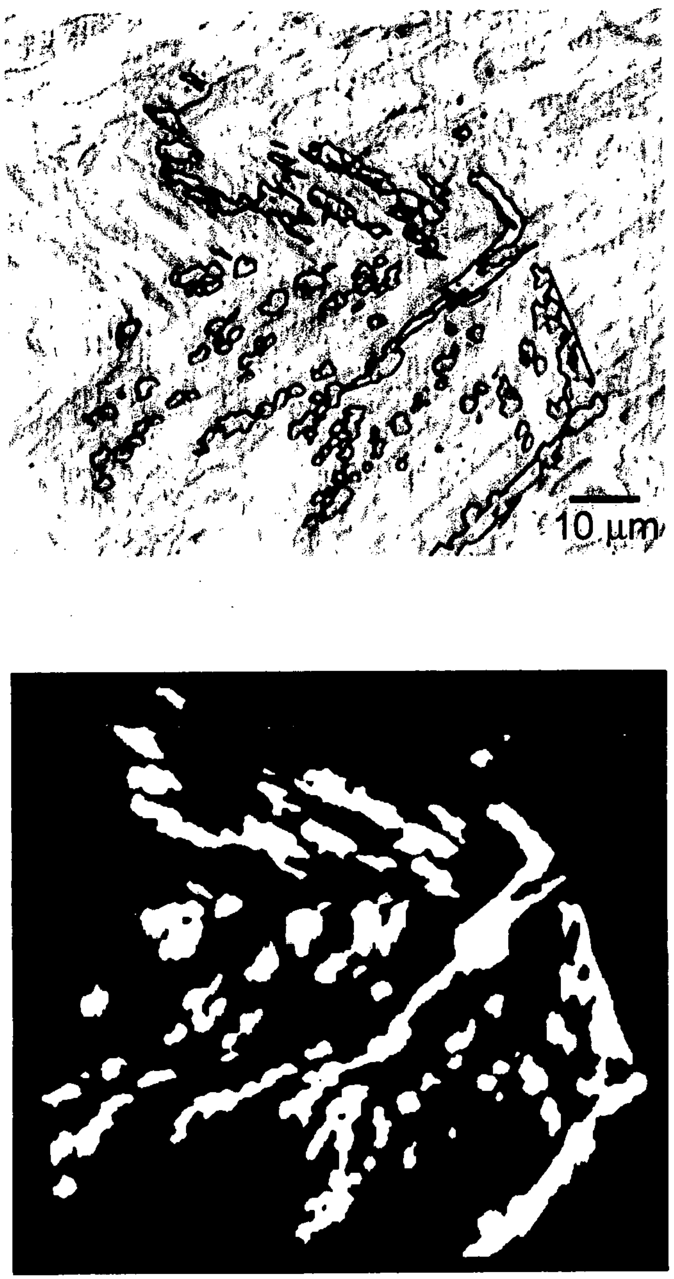




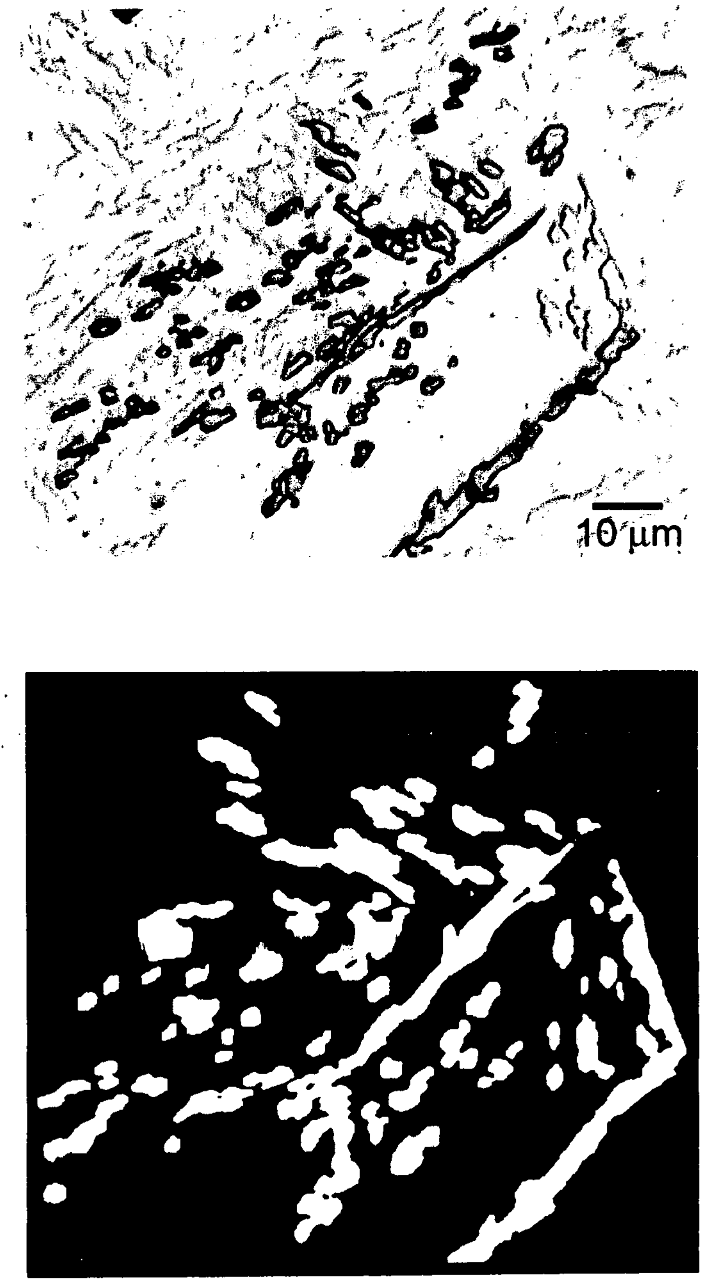
Reconstruction

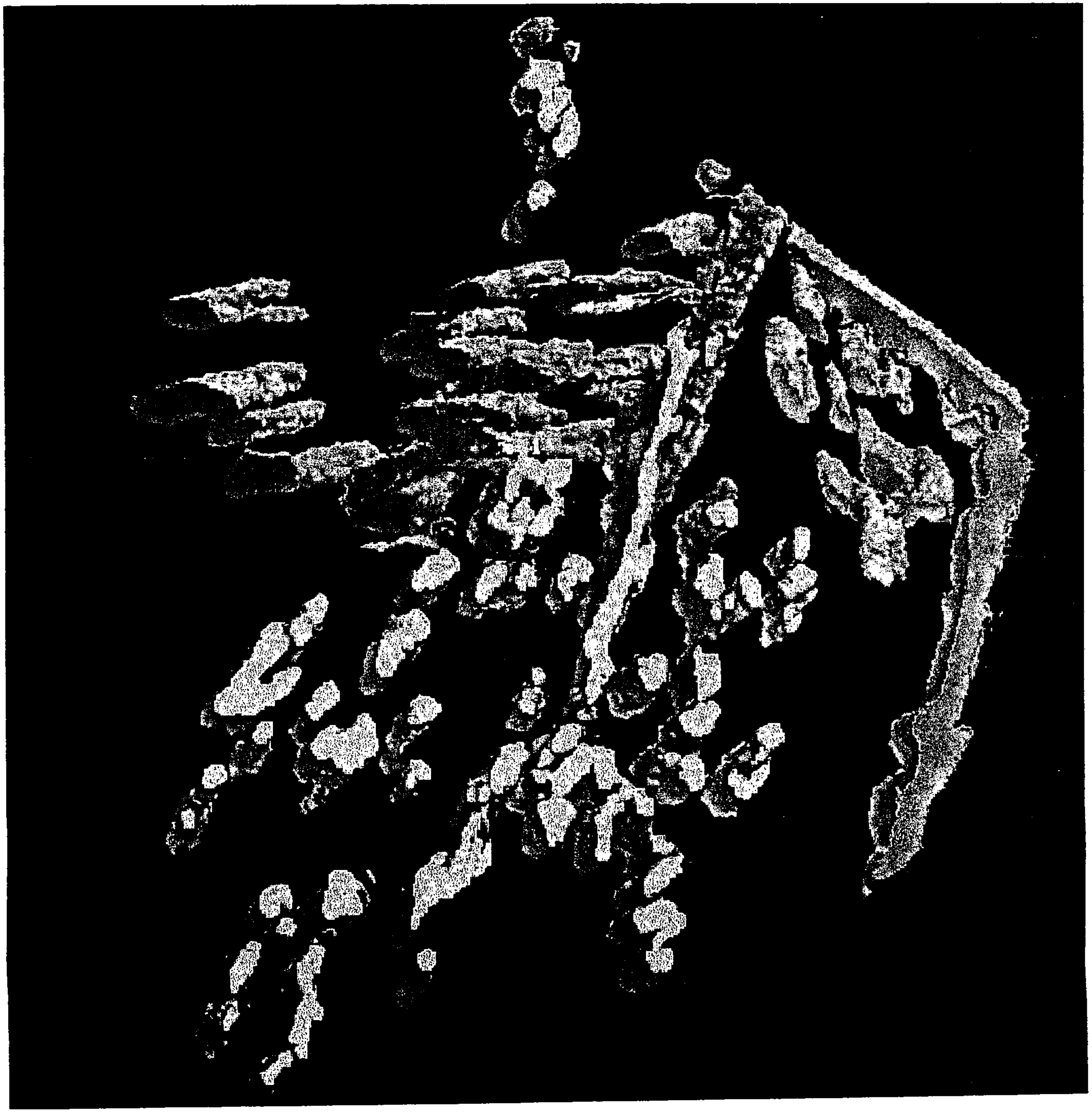
- Slices registered with HV indents and cropped
- Ferrite areas converted to B&W shapes
- Reconstruction with custom-made software

Slice 1



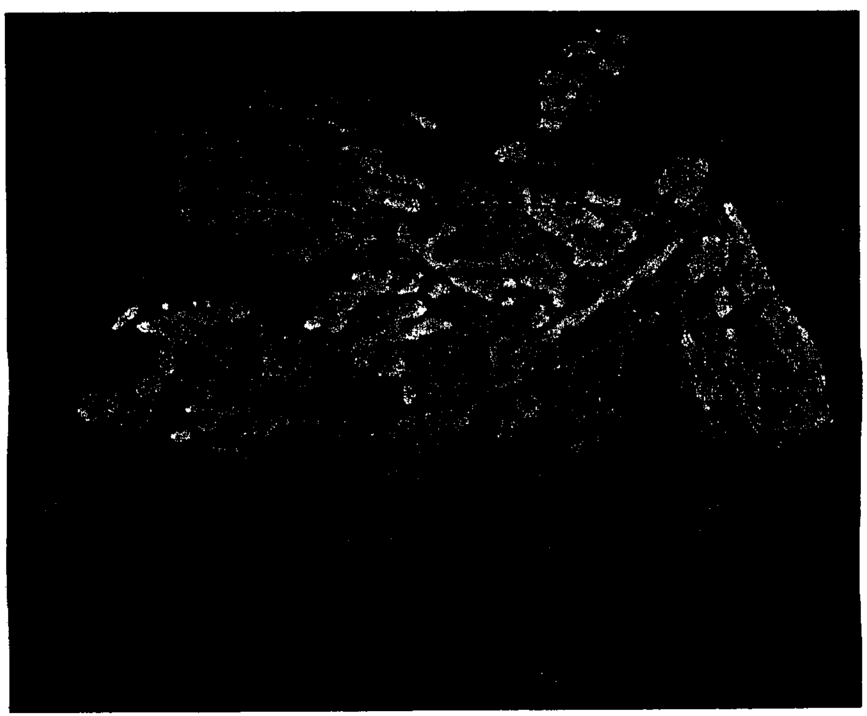
Slice 81

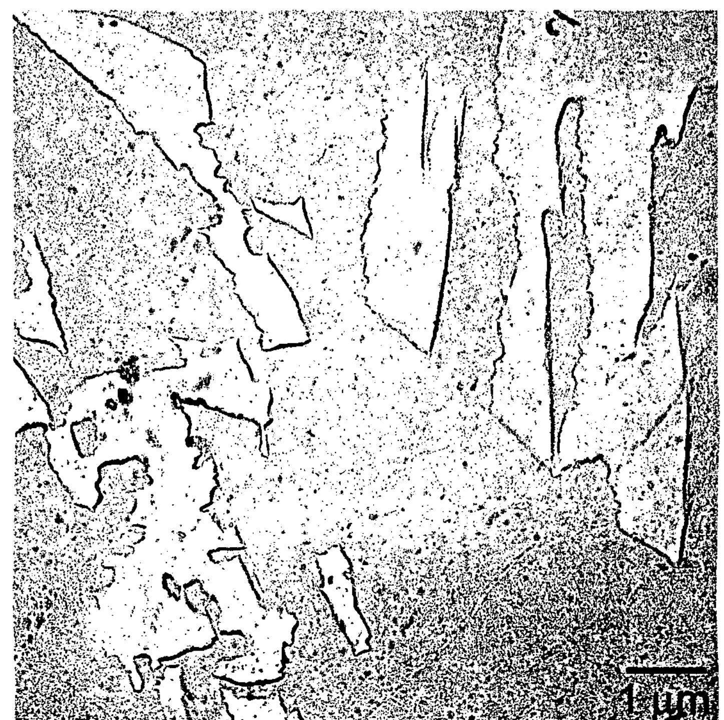




New Information

- Shape
  - *Widmanstatten rods, grouped into sheaves*
  - *Not degenerate*
  - *Rods harder to visualize from 2D sections than plates*
- Preferred growth direction
  - *Angles between sheaves consistent with <310>*
  - *Highlights role of crystallography*
- Connectivity





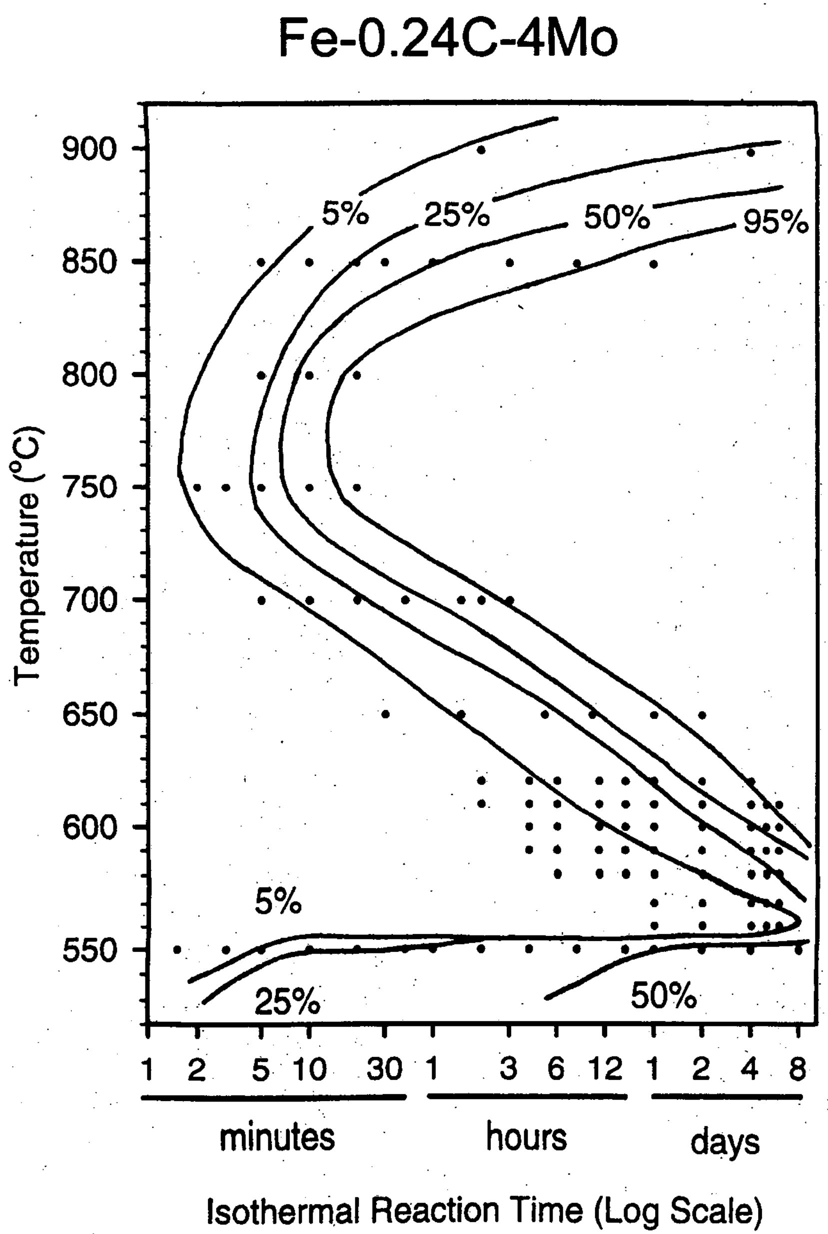
Implications for Reaction Path

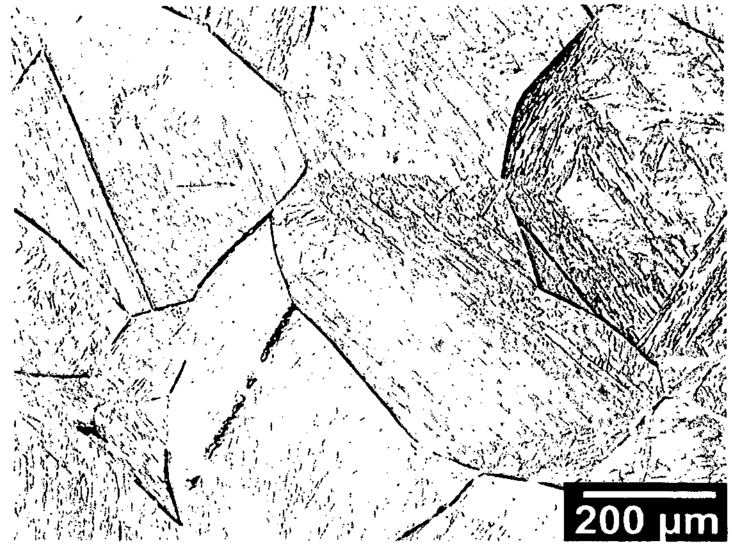
At/Above Bay
- Bainite grows out of GBs and TBs
- Equilibrium M_6C forms early on

Below Bay
- Ferrite rapidly penetrates grain interiors
- Carbide formation delayed
- Metastable M_2C forms later on

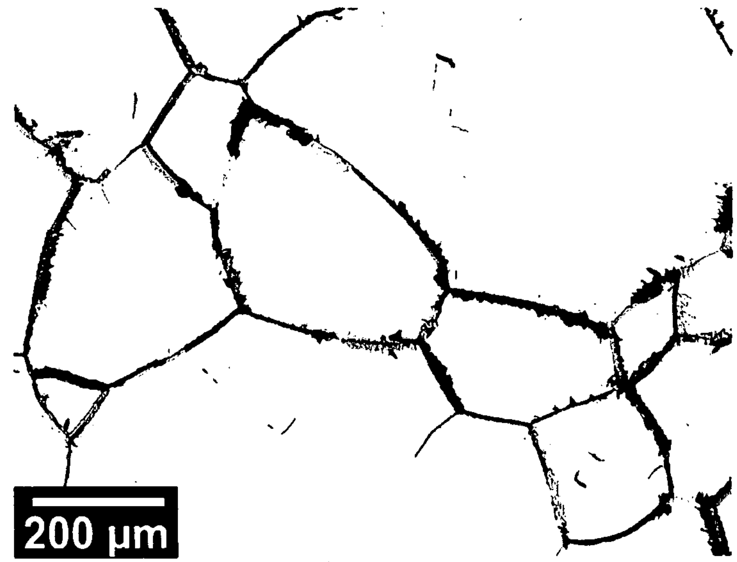
590°C
16 days

Part II: Thickening of Bainite at the Bay





560°C-12 hours



560°C-12 days

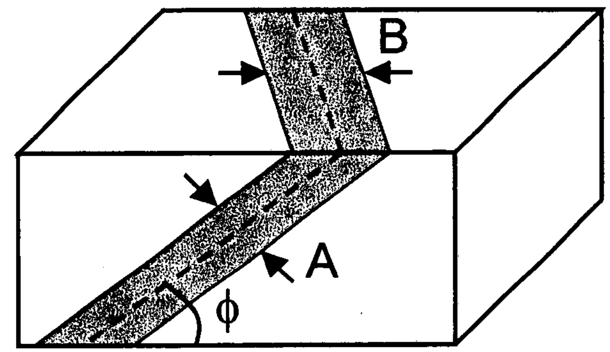
Thickening Measurements in 2-D

Thickening of GB Precipitates

"Largest precipitate technique" often used

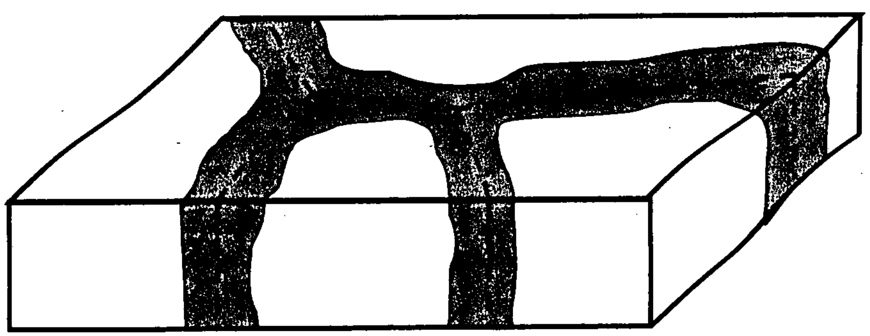
- This assumes the largest precipitate is:
  - *the first to nucleate*
  - *representative (not anomalous)*
  - *sectioned in the plane where it is thickest*

$$A = B \sin(\phi)$$



Stereological issue: angle of GB to plane of polish

- Overcome by the "bamboo specimen technique"
  - *Specimens cold rolled prior to austenitization*
  - *Austenite grains extend through the 250 μm thickness*
  - *Austenite GBs migrate to become perpendicular to faces*

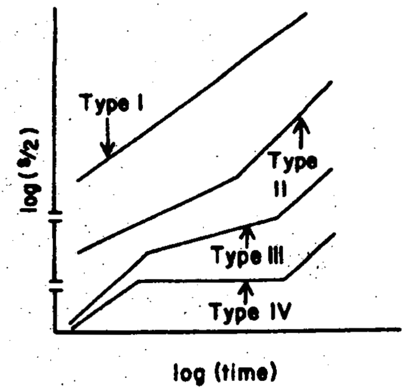


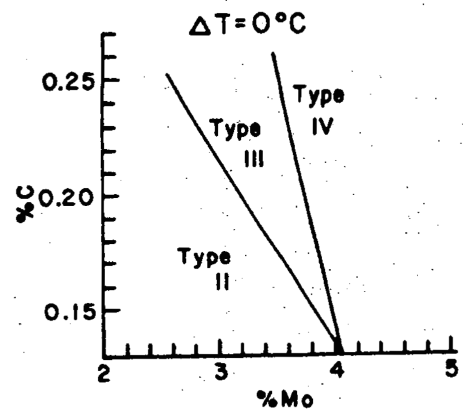
TB precipitates cannot be analyzed this way

Application to Fe-C-Mo

Shiflet and Aaronson (1990)

- 21 alloys reacted at/above the bay
- Four types of GBB thickening
- ↑ C, Mo caused multistage thickening
  - *thickening stasis found*
- No growth models could explain this





Re-examination

Measure thickening in bulk samples

- Explicit angular stereological correction
- Use the same alloy as previous study
  - *Compare growth path envelopes*
- Measure more bainite slabs than just the largest
- Measure TBB thickening

Experimental

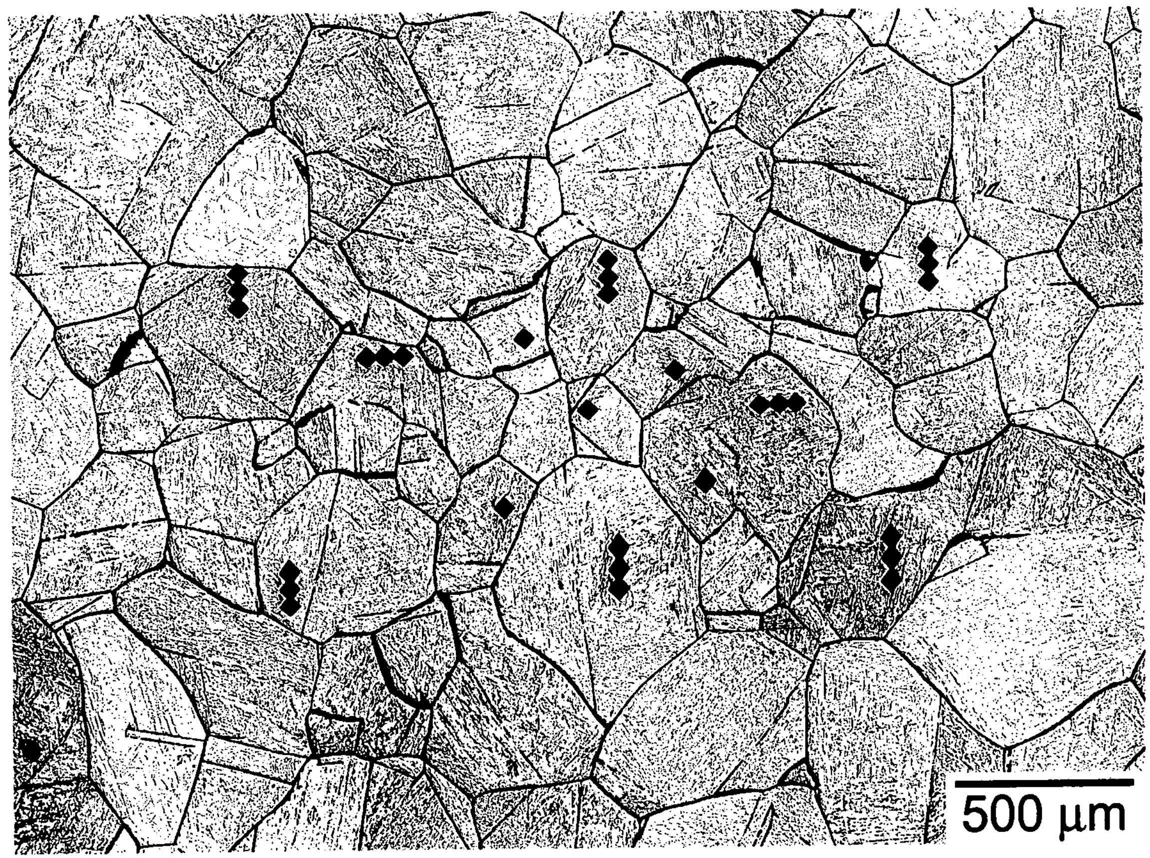
Processing

- Fe-0.24C-4.00Mo (wt%) induction melted, hot worked, homogenized
  - *same ingot used by Shiflet and Aaronson*
- Austenitization at 1200°C, isothermal reaction at bay (560°C), quenched

Sectioning

- HV indents placed
- Light automatic polish
  - *removes HV damage*
- Nital etch
- Digital 3x3 montage taken
  - *3000 x 2300 μm*
- Heavy polish on wheel
  - *removes 7 μm*
- Nital etch

Four sections/heat treatment

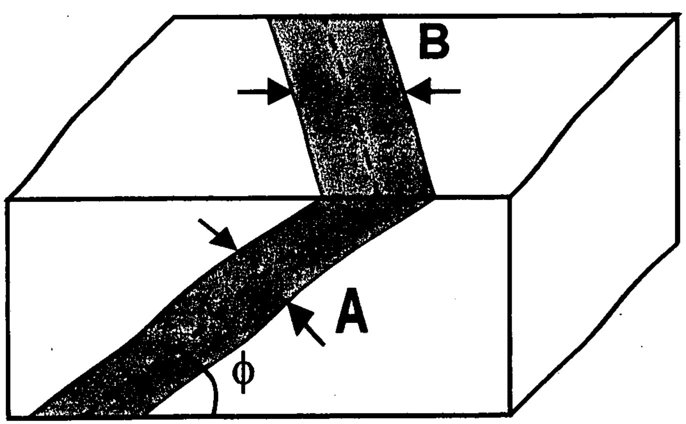


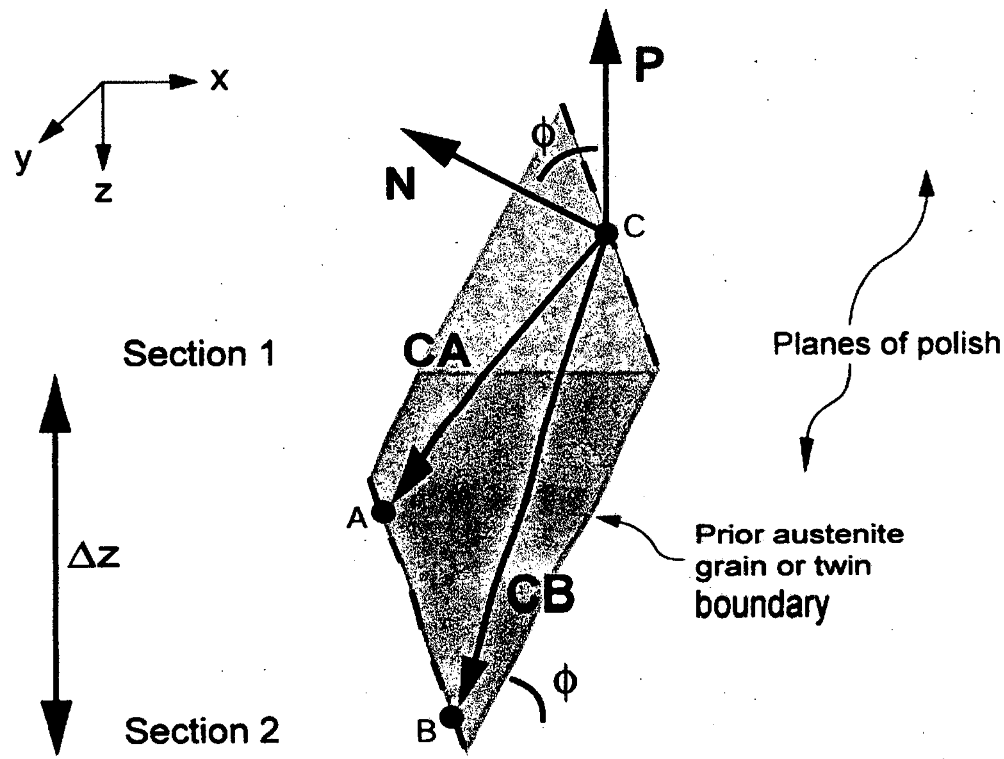
560°C-6 days

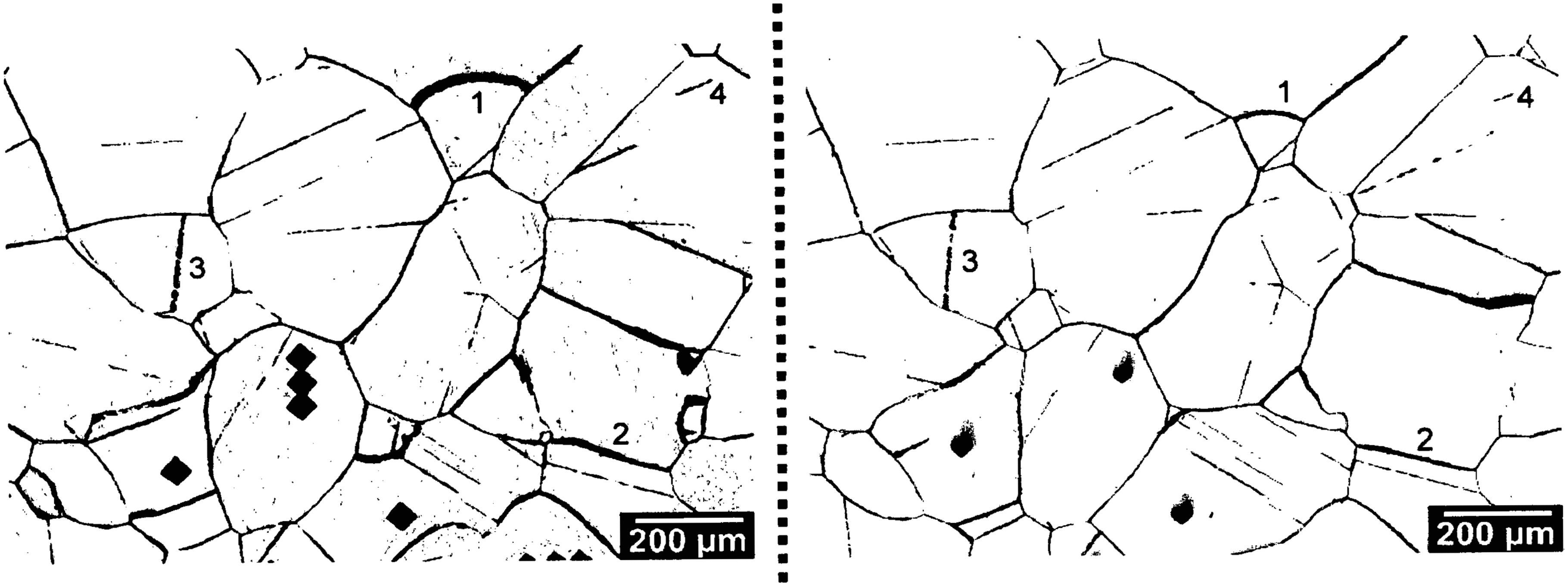
Thickening Measurement

- Every GBB and TBB segment numbered
  - *About 170 GBs and 20 TBs in field of view*
- Apparent thickness **B** measured for top 10 GBB and top 10 TBB
  - *All 4 sections searched*
  - *Segments close to grain corners excluded*
- Four sections aligned using HV indents
- Angle ϕ of the GB or TB plane measured
  - *Depth from HV geometry*
- True thickness **A** calculated

$$\mathbf{A} = \mathbf{B}\sin(\phi)$$





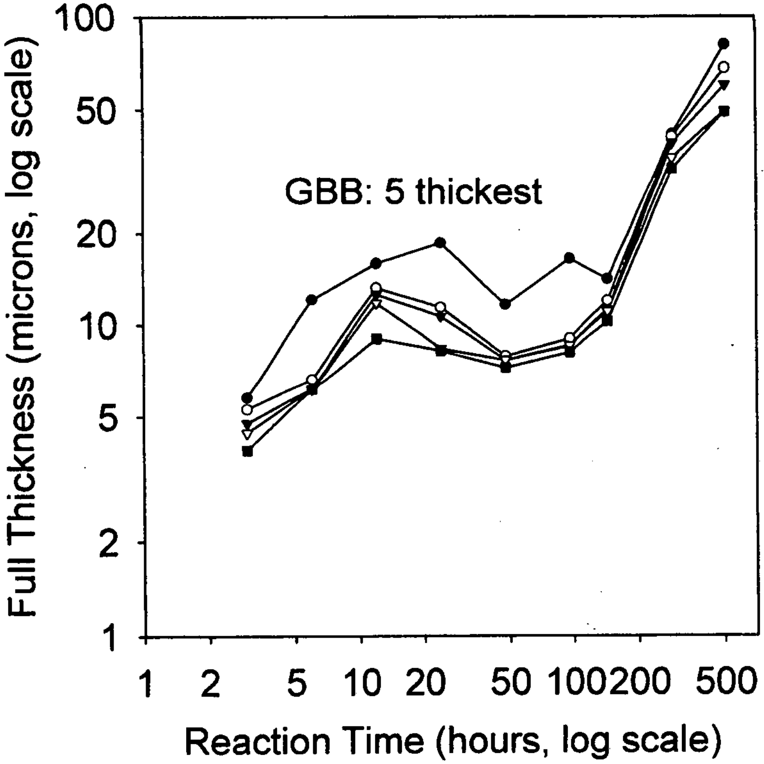


Section 1

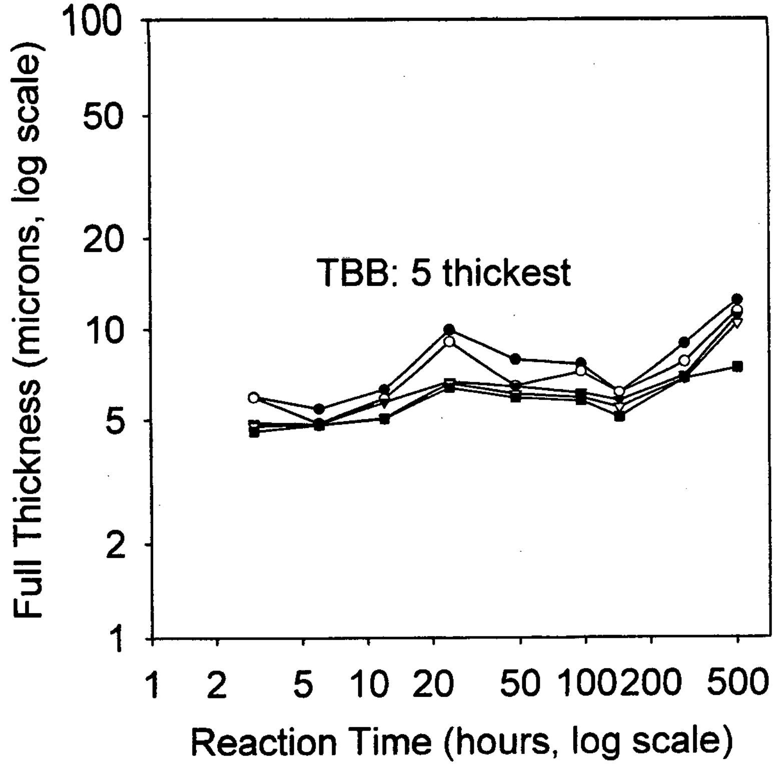
Section 4

$\Delta z = 22.4\ \mu m$

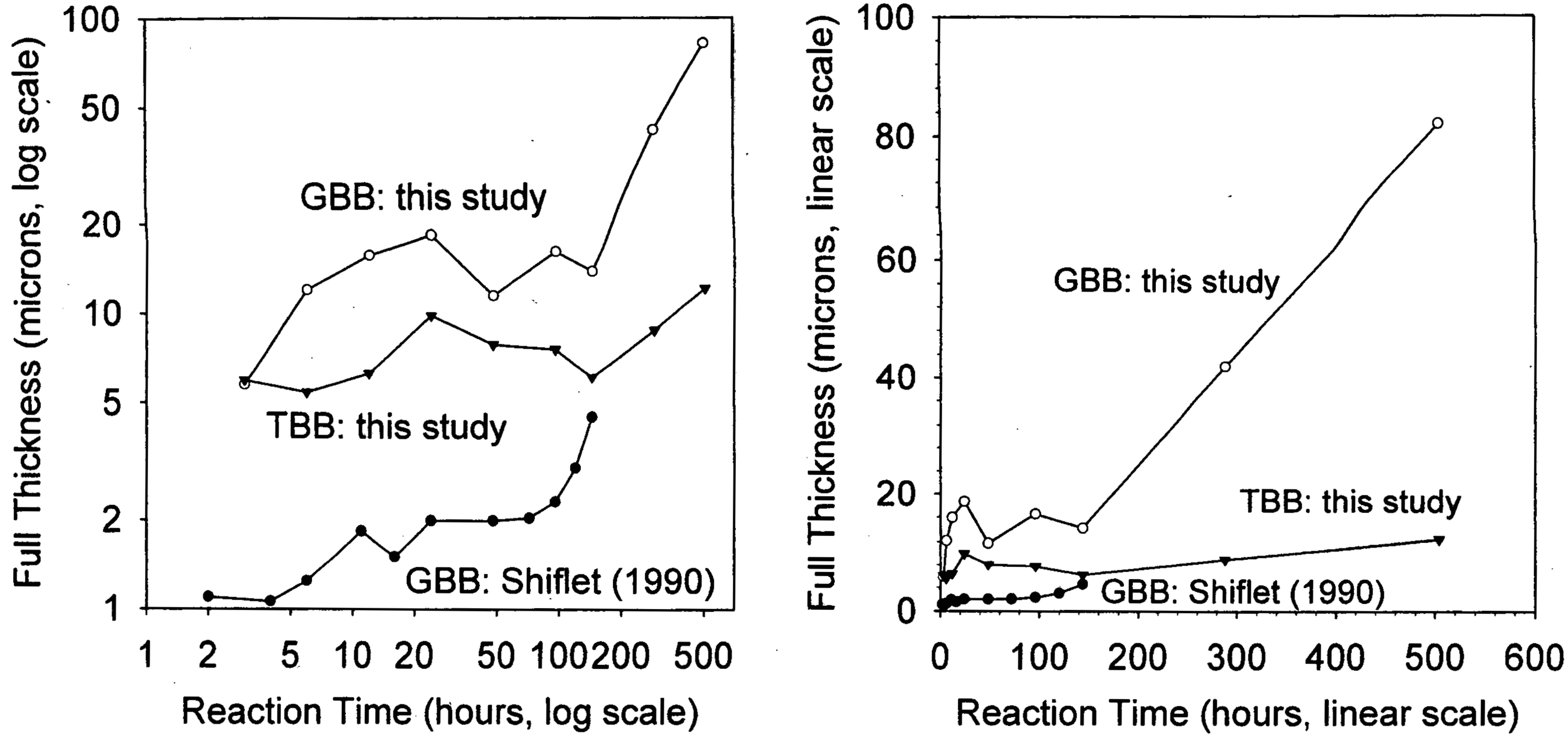
Slab	Angle ϕ	sin (ϕ)	Thickness (μm)		Ranking in Top 10	
			Apparent	True	Apparent	True
GB 1	15	0.26	22.4	5.7	2	10
TB 3	23	0.39	12.8	5.0	1	6



GBB: 5 thickest
Full Thickness (microns, log scale)
Reaction Time (hours, log scale)
100
50
20
10
5
2
1
1
2
5
10
20
50
100
200
500



TBB: 5 thickest
Full Thickness (microns, log scale)
Reaction Time (hours, log scale)
100
50
20
10
5
2
1
1
2
5
10
20
50
100
200
500



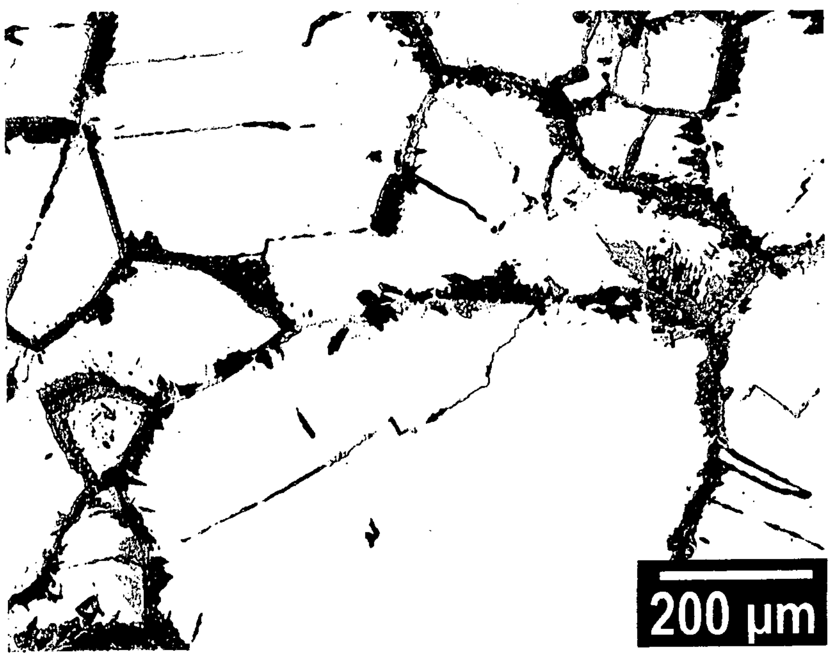
GBB differences between this study and Shiflet & Aaronson (1990)

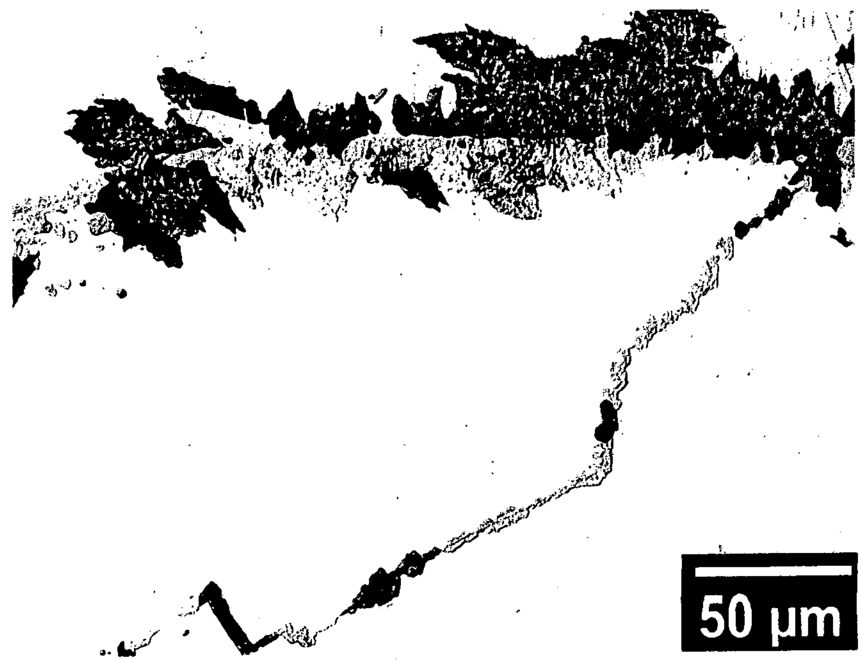
- Different austenitizing temperature
- Intrinsic differences between bulk and bamboo
  - *bamboo GBs free to assume low energy orientations*
  - *Reduction in nucleation (ΔG^*) and growth rates (subunits, ledges/kinks)*

Morphology Considerations

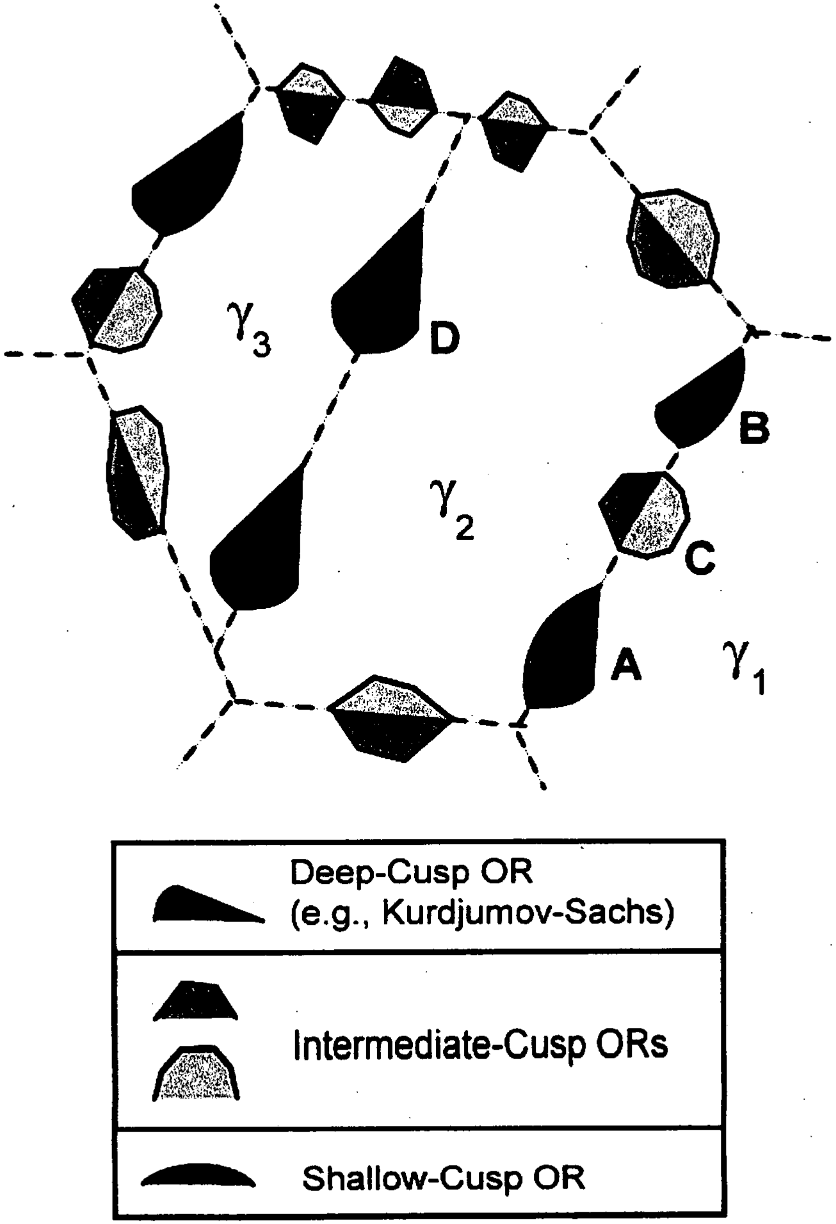
What is the basic unit of growth?

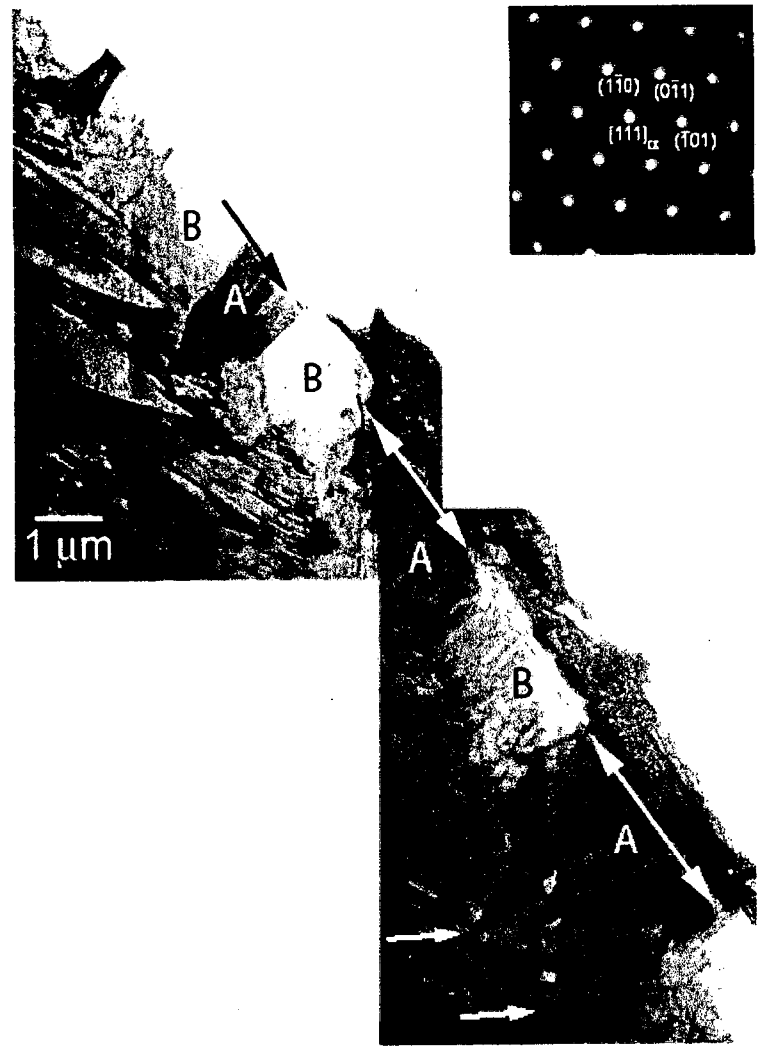
- Prior assumption: ideal monocrystalline allotriomorphic slab
  - *crystallographic effects unimportant*
- Reality: competing subunits
  - *many GBB subunits allow faster overall thickening*
  - *fewer TBB subunits restrict overall thickening*
  - *degree of competition depends on nucleation*





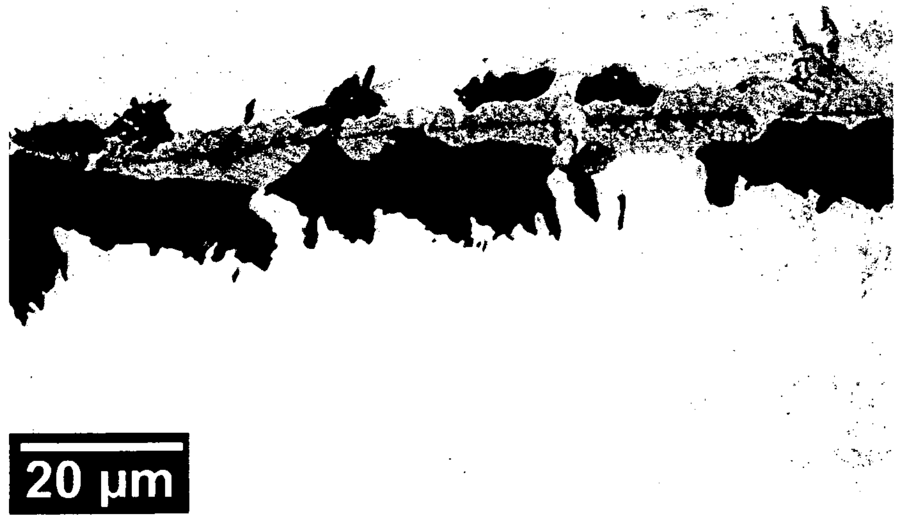
560°C-21 days



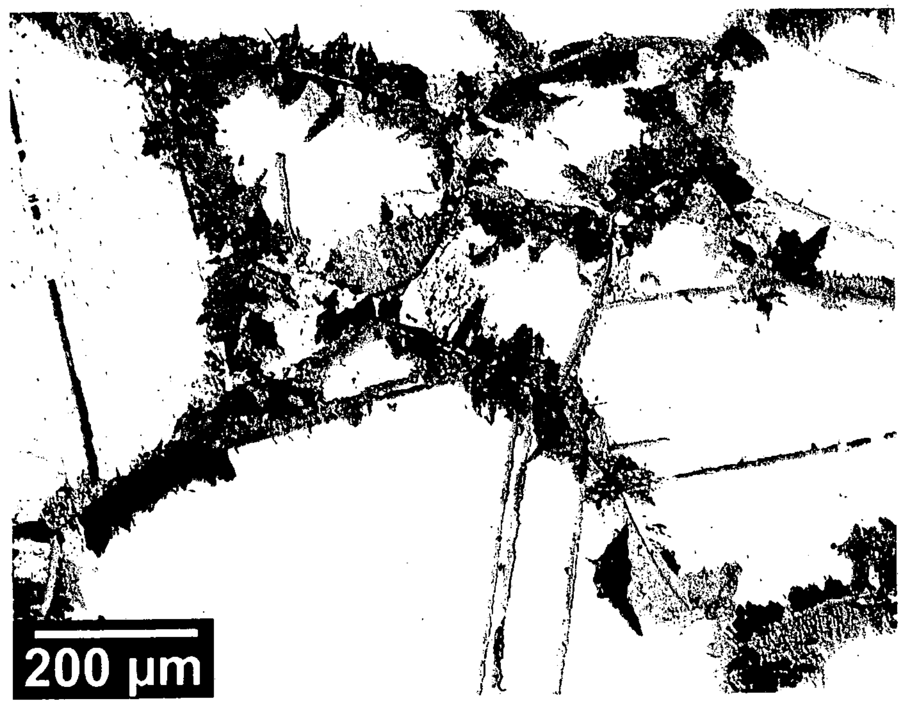


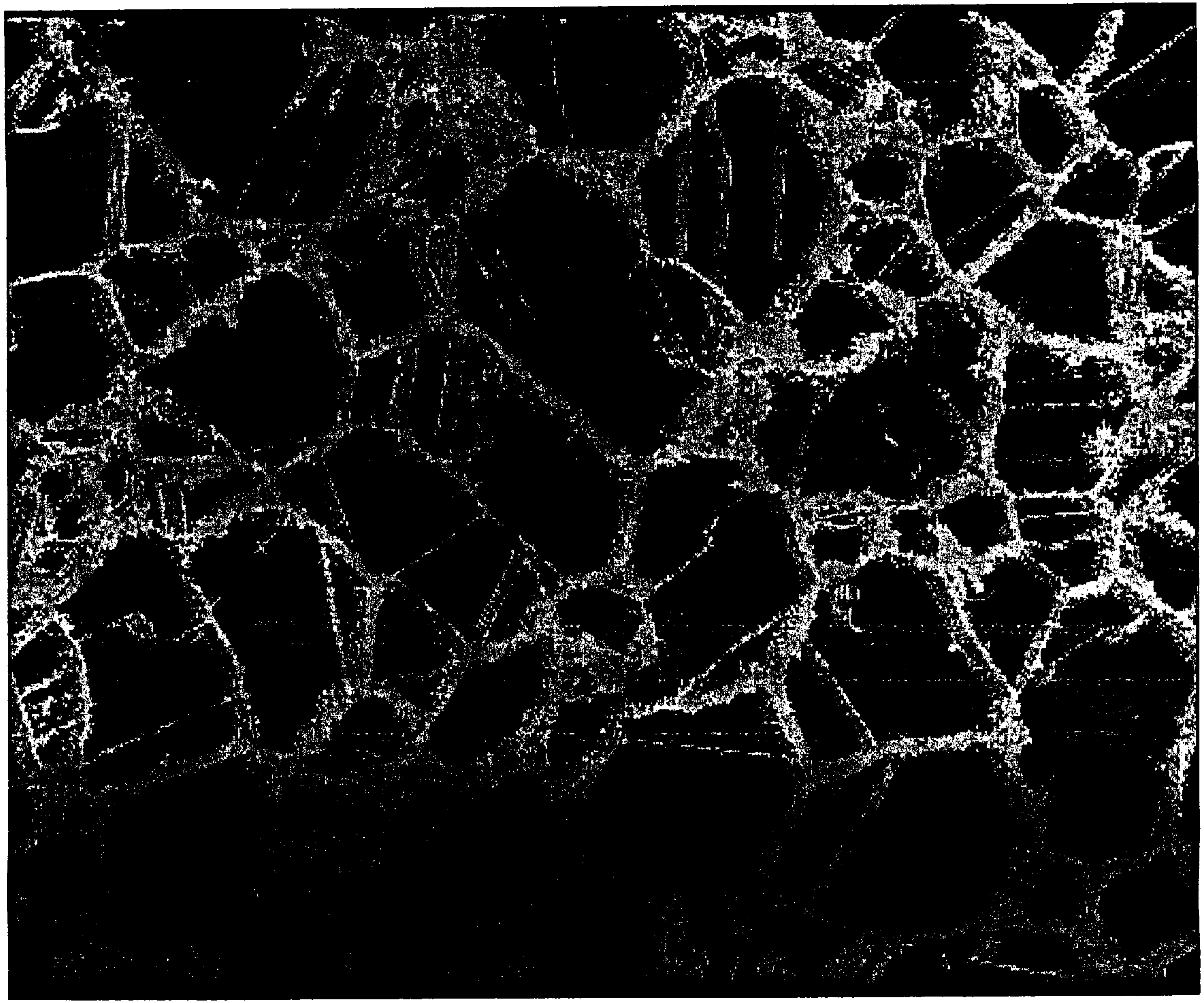
Alternating GBB subunits
560°C-2 days

560°C-12 days



560°C-42 days





Summary

Information from 3-D methods sheds new light on old problems

Bainite morphology below bay in Fe-C-W

- Rods grouped in sheathes
- Role of crystallography highlighted
  - *preferred rod growth directions*
  - *metastable carbide formation*

Bainite thickening at/above bay in Fe-C-Mo

- Explicit stereological correction (bulk samples)
- Test assumptions of "largest precipitate technique"
- Comparison of bamboo vs. bulk
- Measurement of TBB kinetics
- Complemented by optical and TEM
  - *subunit structure*
  - *role of crystallography*